

Properties and Combustion Characteristics of Molded Solid Fuel Particles Prepared by Pyrolytic Gasification or Sawdust Carbonized Carbon

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Pyrolytic gasified charcoal (PGC) and tar are the solid and liquid products, respectively, yielded from biomass gasification technology. In this paper, PGC was molded with adhesives to prepare molded solid fuel (MSF). Tar and PGC were obtained from the pyrolytic gasification of wood chips and sawdust from pine and cedarwood. PGC was molded with phenol resin prepared by wood tar to prepare MSF (MSF-MP). Meanwhile, there were two other methods used to prepare MSF. PGC molded with common phenol resin was one method (MSF-P). PGC was molded with starch adhesive to prepare MSF-S. Wood powder carbonized carbon (WPCC) obtained from the marketplace was employed as a trial sample. The properties and combustion characteristics of MSFs and WPCC were studied. It was found that the shatter strength of these MSFs were more than 95%. MSFs had higher activation energy and comprehensive combustion index compared to WPCC. MSF-MP yielded the following data: shatter strength: 95.86%, lower heating value (LHV): 25.89 MJ·kg⁻¹, ignition: 325 °C, comprehensive combustion index: 1.73×10⁻¹⁰, and activation energy: 61.38 kJ·mol⁻¹. The LHV and activation energy of MSF-MP were superior to those of other MSFs. Therefore, MSF-MP has a market potential for use as barbecue charcoal in restaurant or family gatherings. The preparation of MSF-MP is a prospective method for the utilization of PGC and wood tar.

Keywords: Wood tar; Adhesive; TGA; Biochar; Solid fuels

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INTRODUCTION

With the development of biomass engineering, biomass gasification technology for generating energy has been widely applied in the fields of industry, agriculture, and energy in recent decades. There are by-products in biomass gasification technology, namely non-condensable gas, pyrolytic gasified charcoal (PGC), and tar. However, for a long time, the economic benefit of biomass gasified technology has been limited because the research and utilization of PGC and tar have been insufficient. Biomass gasification poly-generation is an excellent technology based on the three-phase products. Non-condensable gas can be used to generate electric power and heat. PGC is the solid product of biomass gasification and pyrolysis. It can be prepared to make molded solid fuel (MSF), activated carbon, and carbon-based compound fertilizer (Kumar *et al.* 2009; Wu *et al.* 2010; Ma *et al.* 2012). Tar is the liquid product from pyrolyzed gasification of biomass. However, tar and PGC have not been utilized efficiently. In some extreme cases, they are even disposed of as industrial

wastes. Therefore, PGC and tar should be exploited as higher-value products to excavate their potential values and reduce environmental pollution.

In recent years, some researchers have begun studying the disposal of PGC and wood tar. The utilization of tar has continued to perplex researchers, becoming a hot research issue. Amen-Chen *et al.* (1997) studied the separation of phenols from eucalyptus wood tar to determine its main composition and content. Dufour *et al.* (2007) compared two methods of measuring wood pyrolysis tar. Li (2015) used metal catalysts for steam reforming of tar derived from the gasification of lignocelluloses biomass.

Expensive phenol can be replaced by tar to synthesize phenolic resin. This resin can be molded with PGC to prepare MSF, which is helpful to improve the utilization of tar and PGC. However, it has not been studied in depth, and phenol resin synthesized from wood tar has not been applied to MSF prepared from PGC and tar.

In this paper, PGC and tar pyrolytically gasified from wood chips and sawdust were used to prepare MSF. The objectives of this study are to investigate a new kind of MSF using PGC and wood tar and to compare the properties and combustion characteristics of MSF with that of three other home-made or purchased solid fuels.

EXPERIMENTAL

Materials

Pyrolytic gasified charcoal (PGC) and tar were obtained from the suburb of Jiashan in Zhejiang province. With a heating rate of 20 °C/min, wood chips and sawdust of pine and cedarwood were gasified until approximately 780 °C with a holding time of 10 min. The productive rate of PGC and tar is 31% and 1.3%, respectively, based on data coming from the factory. Carbon obtained from the carbonization of wood (WPCC) and Coal with a high lower heating value (LHV) of 32 (MJ·kg⁻¹) were obtained from a marketplace in Nanjing. The solid content and viscosity of phenol resin were 42% and 70 MPa.s, respectively. The phenolic resin modification process was as follows: 20% phenol was replaced by tar containing 42% phenol tested by GC-MS to synthesize phenol resin. Then, this phenolic resin was modified by use of polyvinyl formal solution having a solid content of 15% and a viscosity of polyvinyl formal solution of 31 MPa.s. The amount of polyvinyl formal solution was 10 wt% based on the amount of phenolic resin. The solid content and viscosity of the modified phenol resin were 40% and 120 MPa.s, respectively. Starch adhesive's solid content and viscosity were 9% and 20 MPa.s, respectively. All of the adhesives were synthesized in the lab.

Adhesive Properties

Preparing solid fuel using organic adhesives and PGC is effective because organic adhesives (phenol resin, modified phenol resin, and starch adhesive) and PGC have a good affinity. This affinity means that the adhesion coefficient depends on the characteristics of raw materials (surface free energy and infiltrating activation energy), as well as the bonding strength between raw materials and resin.

In this experiment, the adhesives used to prepare solid molding fuel included phenolic resin, modified phenolic resin, and starch adhesive (MSF-P, MSF-MP, and MSF-S). Phenolic resin has excellent bonding strength, water resistance, heat resistance, wear resistance, and good chemical stability. In the process of modifying phenolic resin, tar was substituted for 20% phenol and reacted with formaldehyde to synthesize phenolic resin.

Then, polyvinyl formal solution was used to modify the resin, facilitating resin bonding with PGC. Polyvinyl formal can improve the flexibility of phenol resin, increase the MSF strength of the composite, and reduce the curing rate and molding pressure. Polyvinyl formal is a super polymer containing various proportions of hydroxyls, aldehyde groups, and acetyl side chains. The property of polyvinyl formal depends on the polyvinyl formal molecular weight, the relative amount of acetyl, aldehyde acetal groups, and hydroxyl groups in the polyvinyl acetal molecular chain, as well as the chemical structure of the aldehyde used.

Preparation of Solid Molding Fuel

After smashing by high speed pulverizer in the lab (RHP-100, Shenlian, China), PGC was filtered with mesh sizes between 0.075 and 0.15 mm to mix with adhesives (phenolic resin, modified phenolic resin, and starch adhesive) manually and molded using a minitype cold press (TER-134, Tongda, China) under 20 MPa pressure, which was held for 2 min. The blended charcoal-to-adhesive mass ratios of MSF-P, MSF-MP, and MSF-S were 1:0.17, 1:0.17, and 1:0.5. Then samples were dried in the oven until a constant weight was obtained. The drying temperatures of MSF-P, MSF-MP, and MSF-S were 140, 140, and 105 °C, and depended on the adhesive's curing temperature. Because the appearance of MSF-P, MSF-MP, and MSF-S was alike, MSF-MP was used as the example. The diameter and density of MSF-MP were 4 cm and 0.82 g/cm³, respectively. MSF-MP is shown in Fig. 2.

The process was as follows:

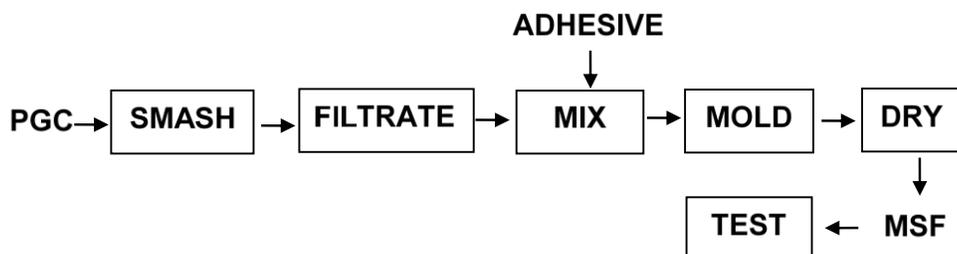


Fig. 1. Flow chart of process MSF



Fig. 2. MSF-MP prepared from pyrolytic gasified charcoal

Product Performance Process

Proximate analysis was performed following ASTM D3172-07a (2007) as a standard. The ultimate analysis was carried out following the CHNS model by a Vario EL elemental analyzer (Vario EL III, Elementar, Germany), and oxygen was estimated by the difference method: $O(\%) = 100\% - C(\%) - H(\%) - N(\%) - S(\%) - \text{Ash}(\%)$. The lower heating values were measured by an oxygen bomb calorimeter (HB-C1000, Hengbo, China). The shatter strength test was performed following DB11/T 541-2008 (2008) as a standard.

Experiments to characterize combustion were performed using a thermogravimetric analyzer (TGA 60AH, SHIMADZU Instrument, Japan). The samples were heated at the rate of 20 °C/min from room-temperature to 850 °C with no holding time. For each test, an accurately weighed 10-mg sample was used, and the flow rate of the carrier gas (high-pure air, purity > 99.99%) was maintained at 70 mL/min. A computer was connected to the TGA and automatically recorded the experimental results for simultaneous analysis of the products with corresponding TGA data. To analyze the properties of PGC, MSFs, and WPCC, the experiments under the same conditions were repeated 10 times to obtain a sufficient replication of data.

RESULTS AND DISCUSSION

Physical and Chemical Properties

With the increase of reaction temperature, wood chips and sawdust can yield more gas than charcoal. Ring-opening reactions and rupture of C-C bonds in the cellulose take place, leading to the evolution of small-molecule gases and condensable volatile compounds.

In the lignin, the side chain of phenol-propane units, as well as C-C, C-O bonds rupture. Devolatilization is enhanced, which leads to increased release of gases. Moreover, gases and condensable volatile compounds may contain C. Therefore, pyrolytic gasification converted wood chips and sawdust into more flammable gases (CO, CH₄, and H₂). This is the reason that the carbon content of PGC were lower than that of WPCC in Table 1 (Hosoya *et al.* 2007; Wang *et al.* 2011b; Ma *et al.* 2015; Hilbers *et al.* 2015).

Table 1. Physical and Chemical Properties

Sample	Proximate analysis (wt.%, db)				Ultimate analysis (wt.%, db)					LHV (MJ/kg ⁻¹)	Exhaust gas	Odor	Combustion stability	Strength (≥ 95%)
	Volatiles	Fixed carbon	Ash	Moisture	[C]	[H]	[O]	[N]	[S]					
PGC	16.00	65.58	5.82	12.60	66.53	1.20	18.49	1.02	0.16	21.74	—	—	—	—
MSF-P	17.80	70.17	5.63	6.40	76.99	1.36	13.68	1.42	0.15	25.63	No	No	No powder	95.37
MSF-MP	18.70	69.33	5.97	6.00	78.65	1.15	13.93	0.15	0.15	25.89	No	No	No powder	95.86
MSF-S	17.80	68.08	6.12	8.00	78.12	1.15	13.11	1.36	0.14	25.53	No	No	No powder	95.48
WPCC	7.00	88.25	3.75	7.54	90.72	0.62	4.28	0.52	0.11	30.45	No	No	No powder	95.23

The main combustible elements of MSF are C and H. These elements dominate calorific value, volatiles, and other related combustion properties. The amount of volatiles in PGC and MSFs seemed to be two and half than that of WPCC. The content of hydrogen in PGC and MSFs was approximately 1 to 2 times higher than that of WPCC. PGC and MSFs also had O contents 3 to 4 times as big as WPCC. Therefore, the bulk of the volatiles are contributed by O and H. WPCC was molded by lignin in wood powder, in which the lignin could be regarded as acting as an adhesive, and then it was carbonized. Traditional carbonization effectively removes oxygen from biomass and improves the energy density of biomass. Therefore, the oxygen content of WPCC was considerably lower than that of PGC.

Because different processes can lead to different elemental contents, the LHV of samples also was different. The LHVs of PGC, MSFs, and WPCC were approximately 22, 26, and 30 MJ/kg⁻¹, respectively. The LHV of MSFs was lower than that of WPCC, which was a comparison. So finding a way to improve LHV of MSFs offers a potential way to satisfy the energy supply in a manner similar to that of WPCC when barbecuing food. Furthermore, high-LHV coal or accelerants can be blended with PGC to improve its LHV when it is processed into MSF. Coal with a high LHV of 32 (MJ·kg⁻¹) was used to prepare high thermal value MSF. The blending proportion of PGC and coal is 1:0.1(10%), 1:0.2(20%), 1:0.3(30%), 1:0.4(40%), and 1:0.5(50%).

The results showed that LHV exhibited an obvious enhancement, increasing from approximately 8.1% to 13.2% in Fig. 3. The heating value was regarded as an overall upward trend. Considering the point of costs and added effects, the most obvious effect was the blending proportion of 20%. The experimental data can provide the certain value that shows how to improve MSF's low heating value PGC in the future (Moon *et al.* 2013; Massaro *et al.* 2014).

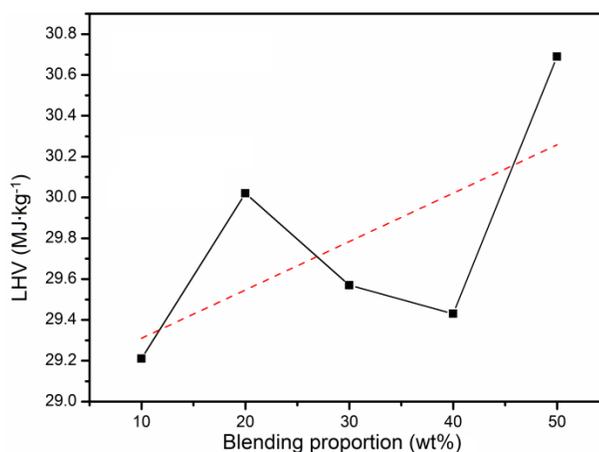


Fig. 3. High-LHV coal blended with PGC

Combustion Characteristics of MSFs and WPCC

TG-DTG analysis of combustion process

There were three main stages of the combustion process in the TG curves of MSFs and WPCC shown in Fig. 4. Moisture evaporation of MSFs and WPCC indicated dehydration in the first step. Secondly, the volatiles were released and combusted. The last

stage was fixed carbon combustion. In the TG curve, there was an obvious cut-off point at the beginning and terminal stage of weight loss. Meanwhile, every curve had only one weight loss gradient. In the dehydrated stage (100 to 300 °C), the weight loss of MSF-S was relatively high: approximately 8%. This was related to large water content of starch adhesive. The main stage of weight loss showed combustion of volatiles and fixed carbon above 300 °C. All MSFs had weight loss peaks from 400 to 500 °C. Obviously, MSF-P had two weight loss peaks, at 412 and 489 °C. The weight loss rates of the two peaks were 0.461%/°C and 0.453%/°C, respectively. The weight loss ratio of MSF-P ranged from 42.4% to 67.8% at temperatures between 412 and 489 °C, respectively. However, the weight loss peak of WPCC appeared above 500 °C. The weight loss rate was 0.412%/°C, and weight loss ratio was approximately 67.24%. This indicates that the thermal stability of WPCC is superior to that of MSFs.

The DTG curve explains the variable relationship between burning rate and temperature in the DTG curves of MSFs and WPCC in the Fig. 4. The peak weight loss rate of one appears earlier, and its maximum rating value is high. These data indicated that the combustion process was relatively fast and its ignition trended toward a minimum. The DTG peaks of MSF-MP and MSF-S appeared relatively later than that of MSF-P. Their weight loss rates were 0.362%/°C and 0.364%/°C, respectively. Wood tar, polyvinyl formal, and starch in the adhesive could help MSF to extend the time of combustion, have a longer combustion time, and reduce the burning rate. Compared with WPCC, MSFs exhibited inflammability, longer combustion time, and lower initial energy consumption. Under combustion in air, the burning residual rates of MSF-MP and MSF-S were 22% and 24%, respectively. However, MSF-P had a lower burning residual rate comparing to other MSFs. Except the ash content of MSF-P, there was only 4 to 5% of fixed carbon remaining in the residual product.

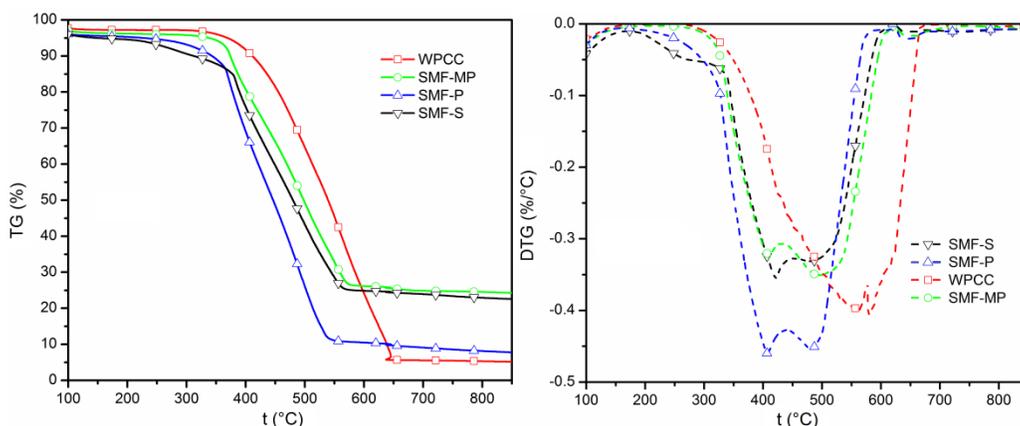


Fig. 4. TG and DTG curves of MSFs and WPCC

Computational analysis of comprehensive combusting characteristics

The ignition temperature was determined by the TG-DTG tangent method, which is suitable for TG-DTG curves in a combusting test. A vertical line is made passing through the weight loss peak of the DTG curve (point A) and intersecting the TG curve at point B. Then, the TG curve tangent at point B intersects with the horizontal line of weight loss beginning at point C. The corresponding temperature at point C is defined as the ignition temperature (point D). Figure 5 demonstrates the method (Jones *et al.* 2015).

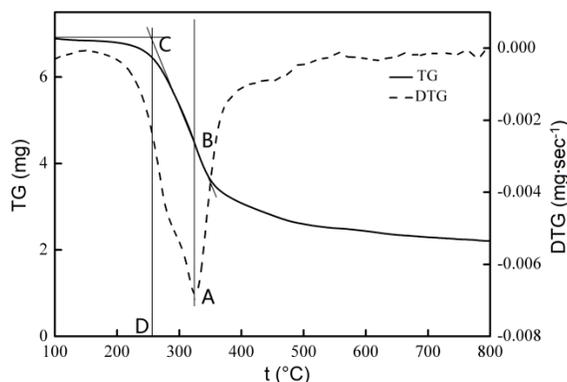


Fig. 5. Schematic diagram of the TG-DTG tangent method for determining ignition temperature

Equation 4 for the comprehensive combustion index is based on the Arrhenius equation, Eq.1:

$$\frac{dw}{dt} = A \exp\left(-\frac{E}{Rt}\right) \quad (1)$$

Equation 1 is differentiated to obtain Eq. 2:

$$\frac{R}{E} \cdot \frac{d}{dt} \left(\frac{dw}{dt} \right) = \left(\frac{dw}{dt} \right) \frac{1}{t^2} \quad (2)$$

Further derivation yields,

$$\frac{R}{E} \cdot \frac{d}{dt} \left(\frac{dw}{dt} \right)_{t=t_i} = \left(\frac{dw}{dt} \right)_{t=t_i} \frac{1}{t_i^2} \quad (3)$$

or,

$$\begin{aligned} \frac{R}{E} \cdot \frac{d}{dt} \left(\frac{dw}{dt} \right)_{t=t_i} & \cdot \frac{(dw/dt)_{\max}}{(dw/dt)_{t=t_i}} \cdot \frac{(dw/dt)_{\text{mean}}}{t_h} \\ & = \frac{(dw/dt)_{\max} (dw/dt)_{\text{mean}}}{t_i^2 t_h} \end{aligned} \quad (4)$$

where $(dw/dt)_{\max}$ is the maximum weight loss rate; $(dw/dt)_{t=t_i}$ is the weight loss rate at the ignition temperature; $(dw/dt)_{\text{mean}}$ is the average weight loss rate; t_i is the ignition temperature; and t_h is the burnout temperature.

Equation 4 is regarded as the formula of comprehensive combustion index (Sun 2002). A higher index means better combustion characteristics. R/E means activity, and a smaller E reveals a higher reaction capacity. $d/dt(dw/dt)_{t=t_i}$ is the conversion ratio of burning velocity at ignition temperature. Its value indicates combusting degree at ignition temperature (Sun 2002). From Table 2, it can be seen that MSF-P and MSF-S were better than MSF-MP and WPCC in terms of combustion efficiency. Further, MSFs molded by PGC showed better combusting performance than WPCC, providing a feasible basis for a mature market product, which finds a possibility that MSF-MP can be used as barbecue charcoal like WPCC in restaurants or family gatherings.

Table 2. Combustion Characteristic Index of MSFs and WPCC

Sample	Ignition temperature (°C)	Burnout temperature (°C)	Maximum weight loss rate (%/°C)	Temperature at maximum weight loss rate (°C)	Average weight loss rate (%/°C)	Comprehensive combustion index
WPCC	400	657	0.412	551	0.0481	1.8852E-10
MSF-P	340	540	0.461	412	0.0913	6.7424E-10
MSF-MP	325	571	0.362	478	0.0228	1.7286E-10
MSF-S	315	560	0.364	423	0.0644	4.2187E-10

Table 2 shows the ignition temperature of MSFs and WPCC. The combustion temperature of starch ranged from 273 to 351 °C, and the weight loss rate reached a maximum at *ca.* 304 °C. The main weight loss temperature range of phenol resin was from 300 to 800 °C, and the heat release rate peak appeared at approximately 545 °C (Zhou *et al.* 2011; Zhang *et al.* 2012). These results reveal that adhesive can affect the ignition temperature of MSFs when PGC and adhesives are mixed and molded. From Table 2, compared with WPCC, MSF-S had a lower ignition temperature. However, the distinction between MSF-P and MSF-MP was the different adhesive. Polyvinyl formal and tar could modify phenol resin to enhance the mechanical strength of MSF. Thermal stability and low flashing point led MSF-MP to speed up decomposition and combustion in a high-temperature environment, endowed MSF-MP with better flammability, and reduced the point of ignition. The ignition temperature of WPCC was 400 °C, and higher fixed carbon meant that WPCC required higher temperatures and thermal energy (Muthuraman *et al.* 2010; Wang *et al.* 2011a; Zhuang *et al.* 2014).

Kinetics analysis of combustion process

Solid reaction kinetics is suitable for combustion process of MSFs and WPCC with a linearly increasing heating rate. The non-isothermal thermal reaction rate equation is shown below, Arrhenius equation,

$$\frac{dw}{d\tau} = A \exp\left(-\frac{E}{RT}\right) f(\alpha) \quad (5)$$

$$\alpha = \frac{m_0 - m}{m_0 - m_\infty} \quad (6)$$

where α is the heat conversion ratio; m_0 is the initial mass of the sample; m is the immediate mass of the sample; m_∞ is the final non-decomposable mass; A is the pre-exponential factor; E is the activation energy; R is the universal gas constant; T is the temperature in Kelvin; $f(\alpha)$ is the differential mechanism function; and α is defined as in Eq. 6.

Kinetics analysis is traditionally expected to produce an adequate kinetic description of the process in terms of the reaction model and the Arrhenius parameters. Various integral kinetic models have been fitted to MSFs and WPCC combustion stage (Zhang *et al.* 2012; Chen *et al.* 2013; Xu *et al.* 2014). To obtain accurate A and E values,

the model free integral method named the Coats-Redfern method is applied in this paper (Coats and Redfern 1964). The Coats-Redfern equation is defined as Eq. 7.

$$\ln\left[\frac{-\ln(1-\alpha)}{T^2}\right] = \ln\left[\frac{AR}{\beta E}\left(1 - \frac{2RT}{E}\right)\right] - \frac{E}{RT} \quad (7)$$

For the average reaction temperature in terms of area and most of the E values, $\frac{E}{RT} \gg 1$ and

$1 - \frac{2RT}{E} \approx 1$, so E can be obtained from the linear plots of $\ln(-\ln(1-a)/T^2)$ vs. $1/T$.

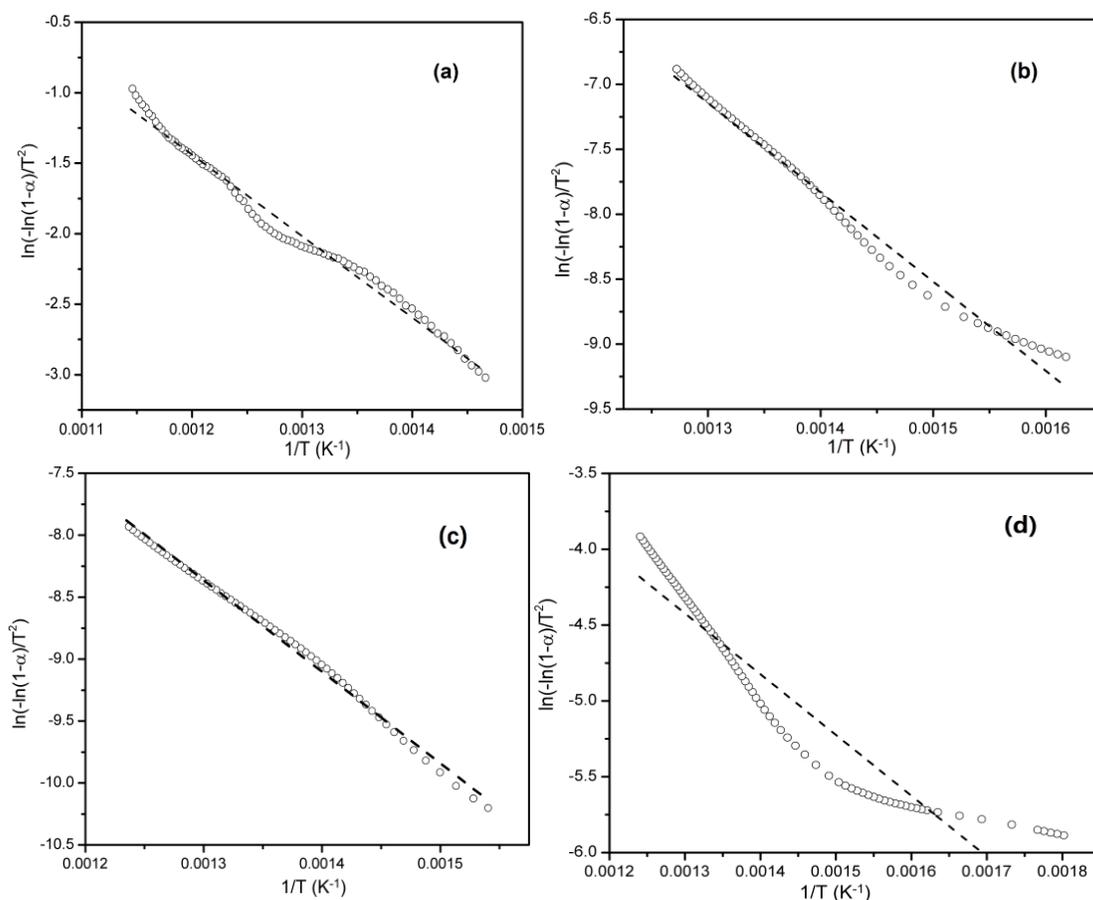


Fig. 6. Arrhenius plots of $\ln(-\ln(1-a)/T^2)$ vs. $1/T$ for MSFs and WPCC at various conversion ratio ranges using the Coats-Redfern method: (a) WPCC, (b) MSF-P, (c) MSF-MP, and (d) MSF-S

Table 3. Activation Energy of MSFs and WPCC

Sample	t (°C)	α (%)	Fitted equation	R^2	A (min ⁻¹)	E (kJ·mol ⁻¹)
WPCC	408-600	0.1-0.8	$y=5.2-5780x$	0.99252	2.0×10^7	48.04
MSF-P	314-514	0.1-0.8	$y=1.8-6876x$	0.99334	9.3×10^5	57.14
MSF-MP	376-536	0.1-0.8	$y=1.2-7386x$	0.99770	8.3×10^5	61.38
MSF-S	281-533	0.1-0.8	$y=0.8-4007x$	0.94271	2.4×10^5	33.30

The Coats-Redfern equation has been widely applied to determine the kinetic parameters associated with non-isothermal thermoanalytical rate measurements. In the current study, the Coats-Redfern equation was used to analyze the data obtained in TGA, as there have been few reports on the kinetic modeling of flaming decomposition of PGC, MSFs, and WPCC. Figure 6 shows the Arrhenius spectra with conversion ratio varying from 0.1 to 0.8 using the Coats-Redfern method. It shows a good linear dependence on Arrhenius plots of $\ln(-\ln(1-a)/T^2)$ vs. $1/T$ for MSFs and WPCC. The linear coefficient of determination (R^2) was over 0.90. The R^2 of MSF-MP was 0.9977. This shows that the kinetics parameters achieved a high credibility and the Coats-Redfern method was suitable for samples pyrolyzed in the high-temperature range. Pyrolytic samples can be described as a first-order reaction process. The results by Coats-Redfern method are shown in Table 3. Activation energy is the amount of energy needed when molecules from normal state to active state where chemical reactions happen easily. As can be seen in Table 3, the burning activation energy of samples were calculated when the conversion rate (a) was 0.1. The energy needed by MSF-S was relatively low, and it was the easiest to ignite. Because of the use of different adhesives, the activation energies of MSFs also revealed differences. MSF-MP had the highest E value, $61.38 \text{ kJ}\cdot\text{mol}^{-1}$. As a whole, the E values of MSFs were higher than that of WPCC. A is a constant that depends only on the nature of reaction and samples and has nothing to do with the reaction temperature and material concentration in the system. A is one of the important parameters of kinetics and expresses the intensity of the reaction. Among the samples, the A values of the WPCCs outclassed those of the MSFs, and MSF-MP was in the middle (Zheng and Kozinski 2000; Ouyang *et al.* 2013).

CONCLUSIONS

1. Using phenol resin, modified phenol resin, and starch adhesive, pyrolytic gasified charcoal (PGC) was converted to molded solid fuel (MSF) particles. Compared to the other two MSFs and wood powder carbonized carbon (WPCC), MSF-S, prepared with a starch binder, exhibited better inflammability and comprehensive combustion index: LHV: $25.53 \text{ MJ}\cdot\text{kg}^{-1}$, ignition: $315 \text{ }^\circ\text{C}$, comprehensive combustion index: 4.22×10^{-10} , and activation energy: $33.30 \text{ kJ}\cdot\text{mol}^{-1}$.
2. According to the TG-DTG curve, combustion characteristics, combustion dynamics model fitting equation, and related kinetic parameters obtained were analyzed comprehensively. The coefficient of determination for a linear fitting equation was higher than 0.99. The activation energies of MSF-P (prepared with phenolic resin) and MSF-MP (prepared with modified phenolic resin, incorporating polyvinyl formal) were 57.14 and $61.38 \text{ kJ}\cdot\text{mol}^{-1}$, respectively. The pre-exponential factors of MSF-P and MSF-MP were 9.3×10^5 and $8.3 \times 10^5 \text{ min}^{-1}$, respectively. Through a first-order reaction kinetics model, the combustion characteristics of MSFs were further examined, providing a theoretical basis for the development of gasification poly-generation technology.
3. In this work a new approach of producing MSFs by using PGC and wood tar is presented. The results tested in this work are similar to other MSFs and WPCC, showing that MSF-MP prepared by this method may have the possibility that MSF-MP used as barbecue charcoal like WPCC. The data of MSF-MP showed: shatter strength:

95.86%, LHV: 25.89 MJ·kg⁻¹, ignition: 325 °C, comprehensive combustion index: 1.7286×10⁻¹⁰, and activation energy: 61.38 kJ·mol⁻¹.

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